

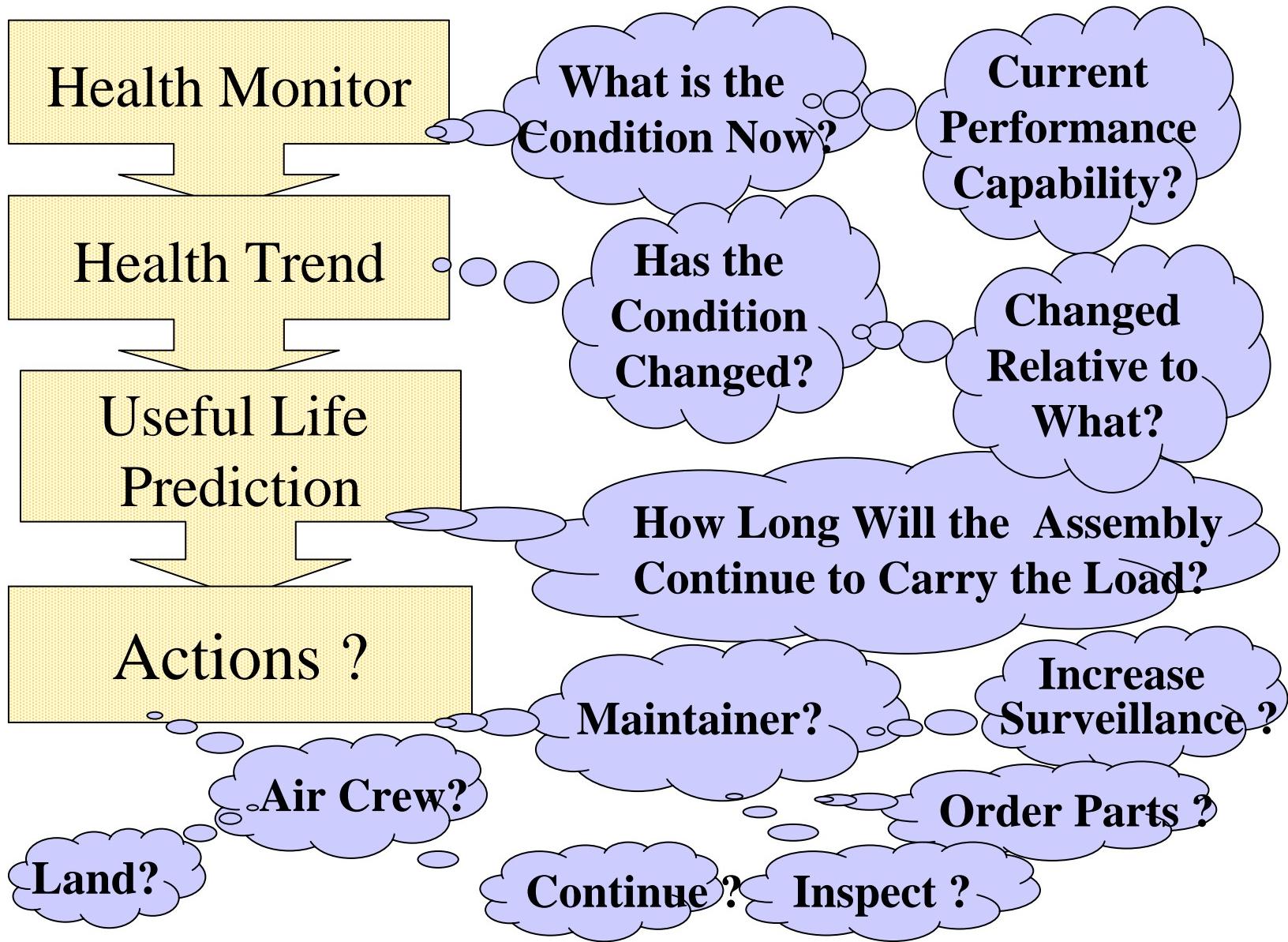
# A Prognostic Development Methodology with Demonstration Examples

**DARPA/DSO Prognosis Bidder's Conference**  
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**Propulsion and Power**  
**Naval Air Systems Command**

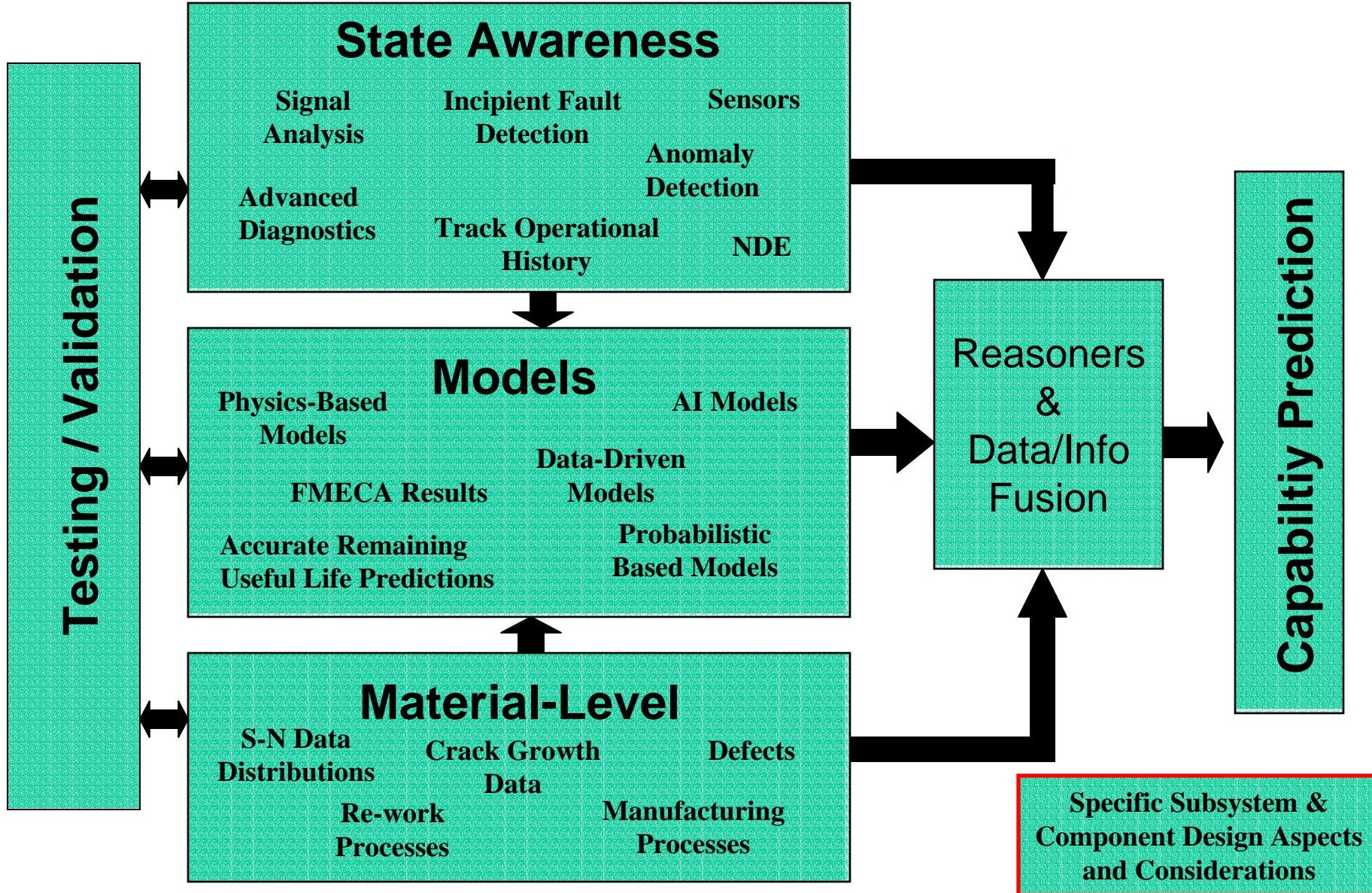
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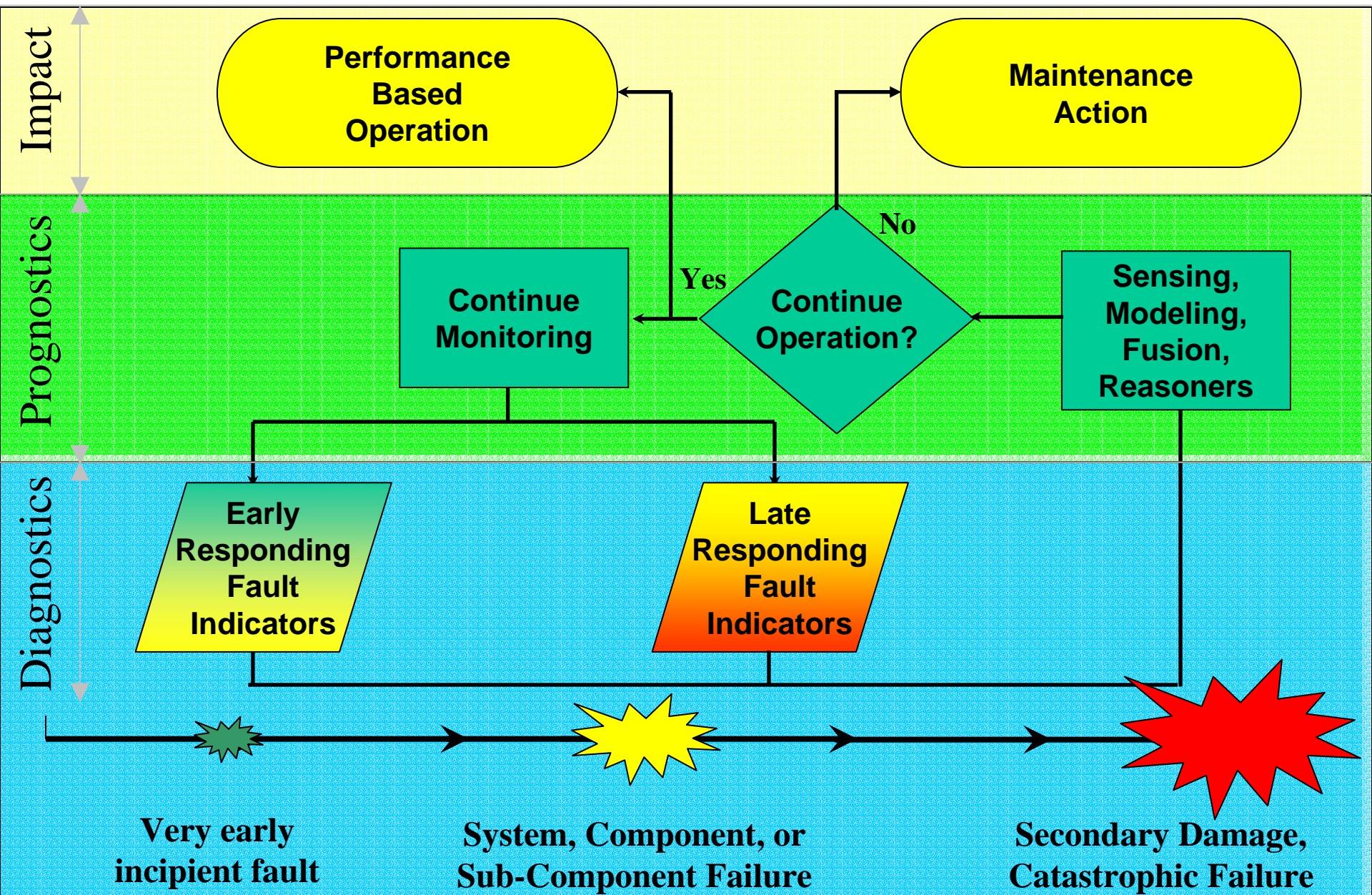


# Prognostics Tool Kit or “Bag of Tricks”

- Accurate/sensitive sensors, algorithms, indicators
- Multiple independent indicators and analysis
- Model based techniques
  - Detailed understanding of the physical system
  - Normal and degraded failure conditions
- Determination of component health at any point in time
- Incorporation of FMECA results
- Impact of secondary component damage
- Techniques for data scatter and false alarms
  - Fuzzy logic, neural networks, AI
  - Data/Information fusion
- Reasoners



# Fault Management Process and Timeline



- Using diagnostic algorithms and techniques
- Intelligent setting of alarm thresholds
  - Cockpit and maintenance
- Elimination of false alarms
- Signature deconvolution to extract incipient fault signatures and “see” precursors to component failure
- Extrapolation of diagnostic indicators and statistical data enabling trending and failure predictions
- Need to understand failure progression rates
  - Knowledge base of experienced failures
  - “Seeded fault” data base
  - Accurate models

# Notional Strategy to Demo Predictive Prognostics on Helo Drivetrain

1. Identify and Target Components and Sub-elements suitable for Prognostics
  - Those with understandable fault to failure progression characteristics
  - Eliminate those impossible or too hard to consider
2. Develop and/or Obtain advanced models
  - Fault to failure progression characteristics
  - Useful life remaining
3. Perform experimental seeded fault tests
  - As many as affordable/beneficial
  - Try to understand the physics of the failure
4. Verify and validate models
  - Seeded fault and
  - Blind test data
5. Modify useful life remaining prediction model to account for real world considerations
  - Mission Profiles
  - Operational Environment
  - Operational History

# Helicopter Transmission Test Facility

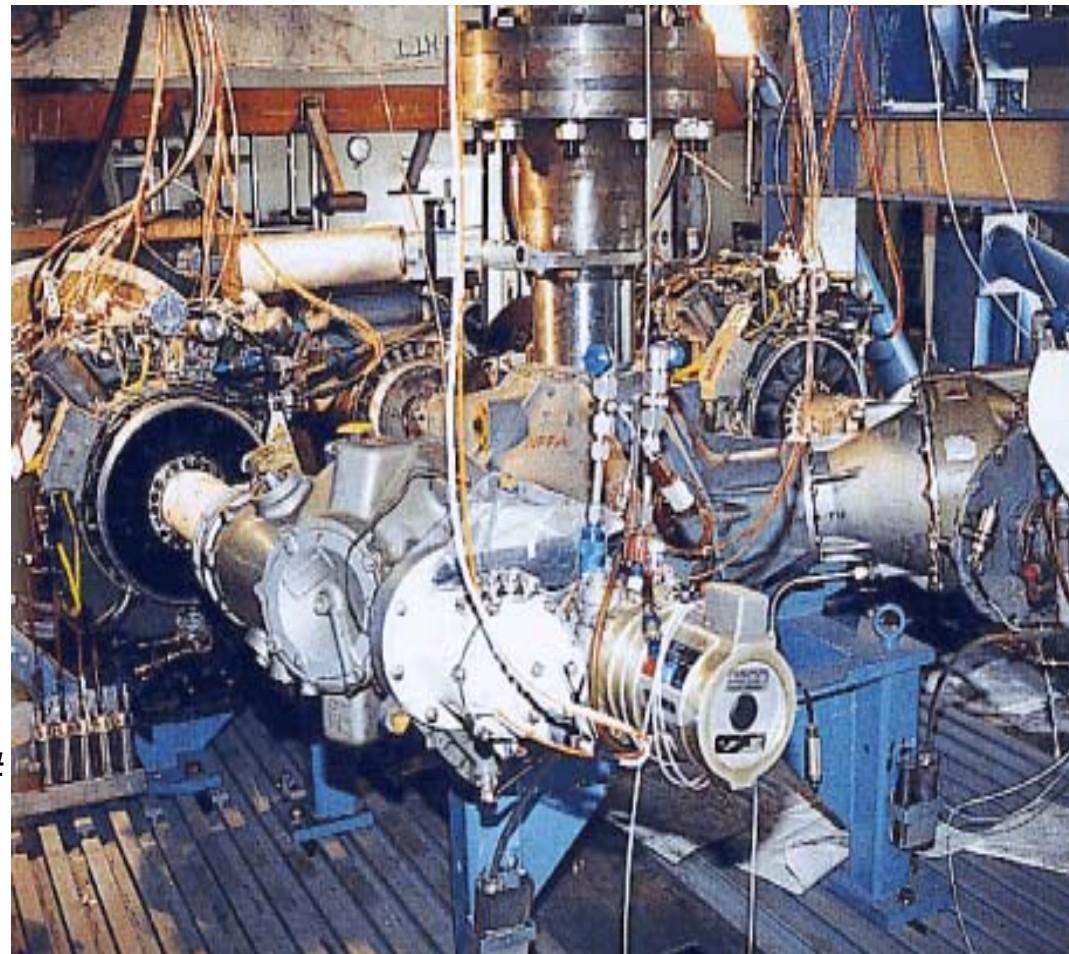
## SH-60 Drive System Config:

- Two T700 Engines
- Dual Engine Ops and OEI
- Main Gearbox
- Input Modules
- Accessory Modules
  - Generators
  - Hydraulic Pumps
- Tail Drive System
  - Oil Cooler, IGB, TGB,  
Shafting & Rotor Brake

## Aircraft Loads Simulated

- Main Rotor Load - 8,000 SHP
- Main Rotor Lift - 50,000 #
- Main Rotor Bending - 5,000 #
- Tail Rotor Load - 700 SHP
- Accessories
- Rotor Brake

## “Diagnostics Laboratory”



## *Objective*

- Investigate and develop initial recommendations on integral elements for a predictive prognostic development strategy
  - Seeded fault testing
  - Physical and statistical based modeling
  - Finite element analysis
  - Material science and understanding physics of failures
- Establish baseline capability for prediction of system level useful life and performance capabilities

## *Procedure*

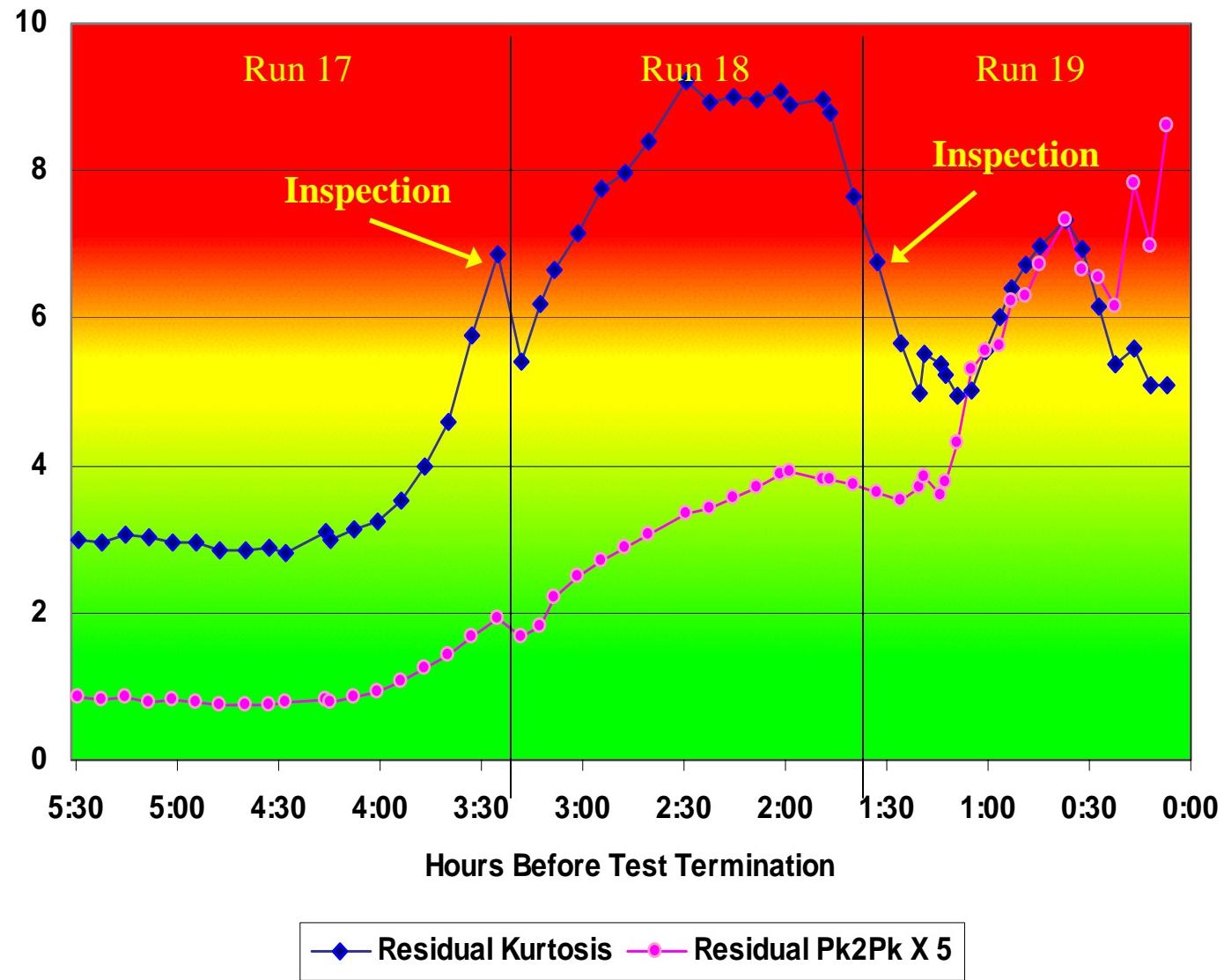
- Create stress riser in gear to induce crack
- Run gear at Pax River HTTF until just before catastrophic gearbox failure
- Inspect at regular intervals
- Attempt to:
  - Measure crack size and determine crack propagation rates
  - Predict remaining useful life
  - Obtain better understand the physics of failure for this component



EDM Notch (0.25" L x 0.04" D x 0.005" W)

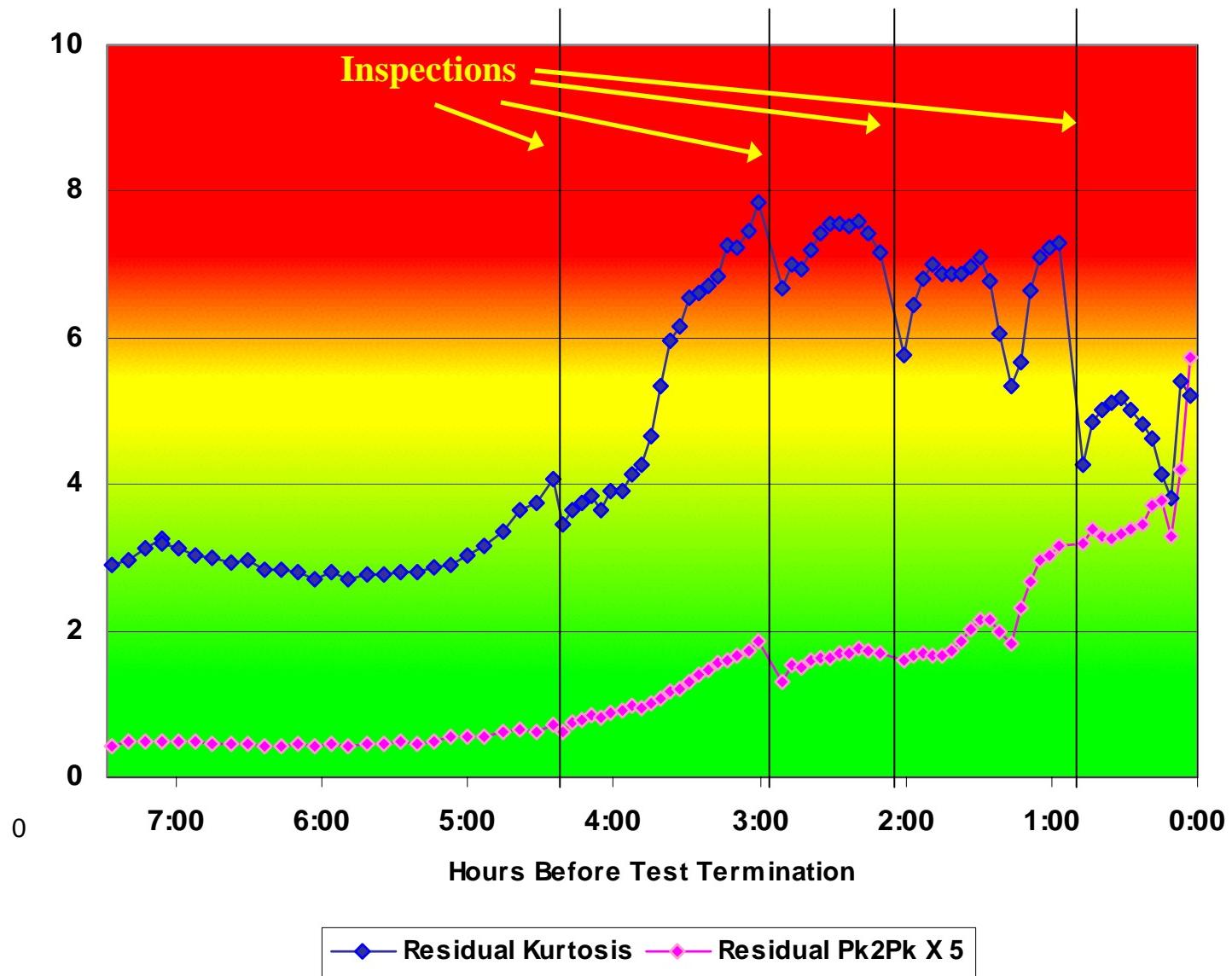
# Intermediate Gearbox Pinion Crack Test

## Inspections based on hours



# Intermediate Gearbox Pinion Crack Test

## Inspections Based on Condition Indicators



# H-60 IGB Pinion Gear Surface Inspection

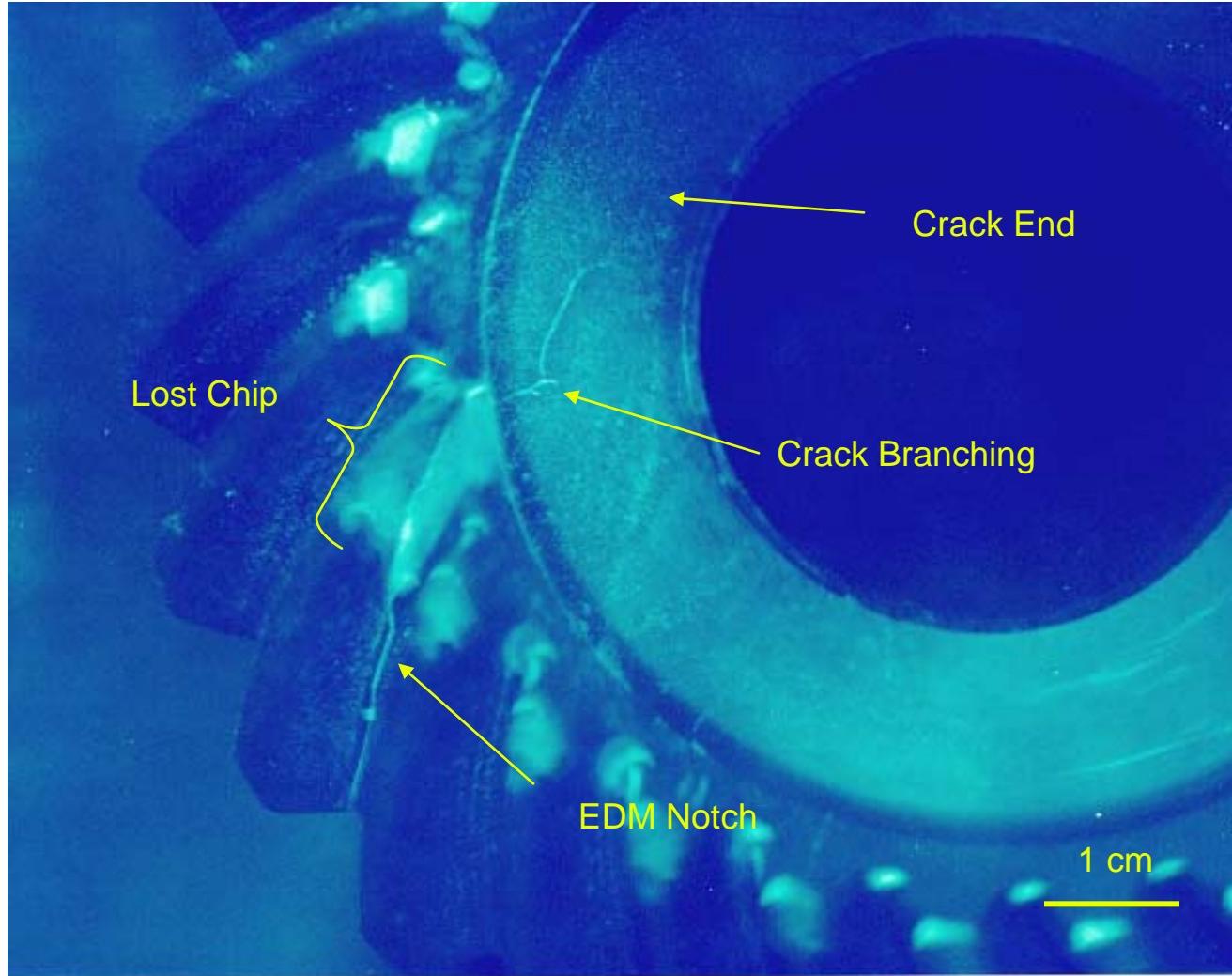


Image of heel notch inner end after Run 15 (first test), showing small chip liberated (arrow). No noticeable change until run 18.

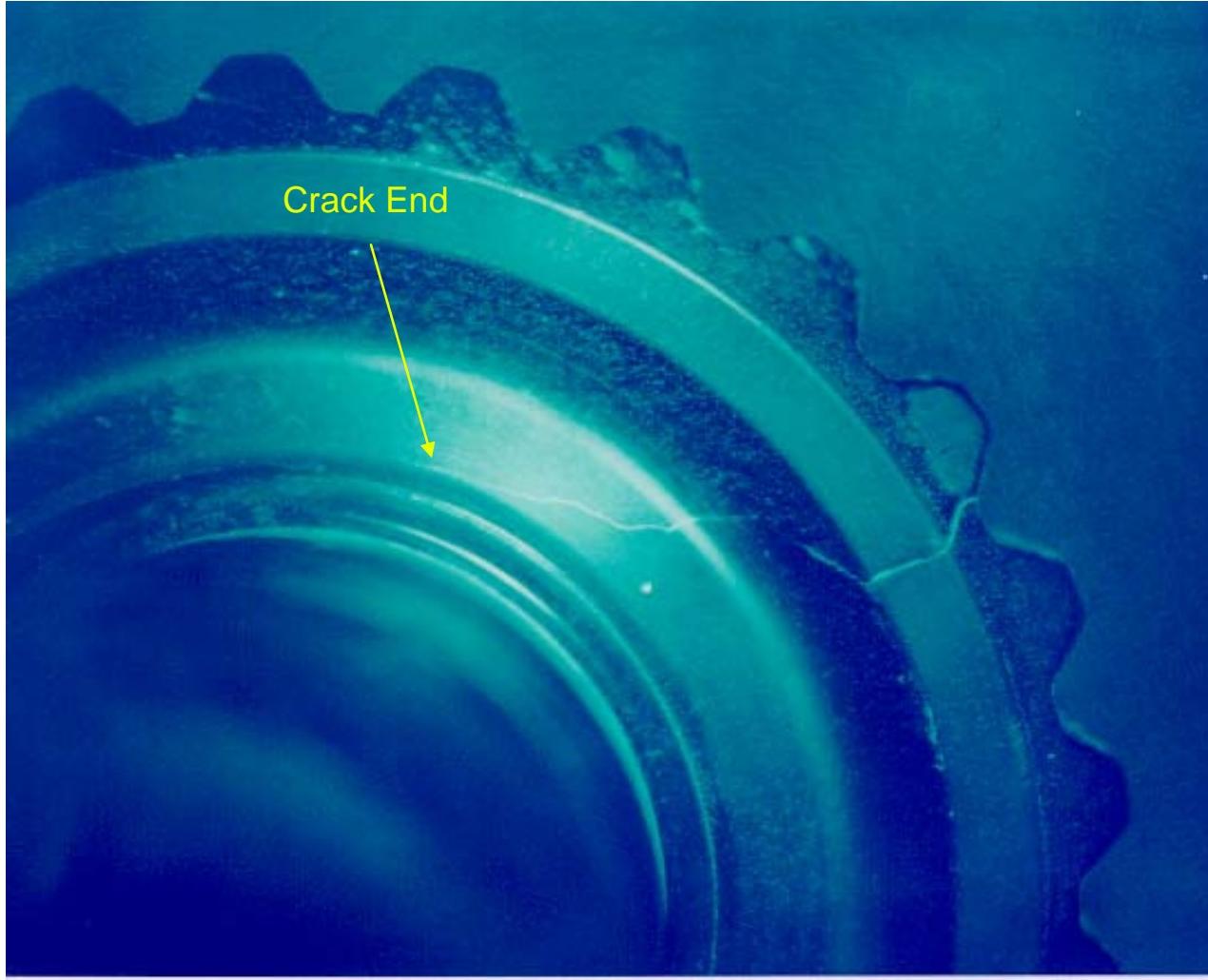


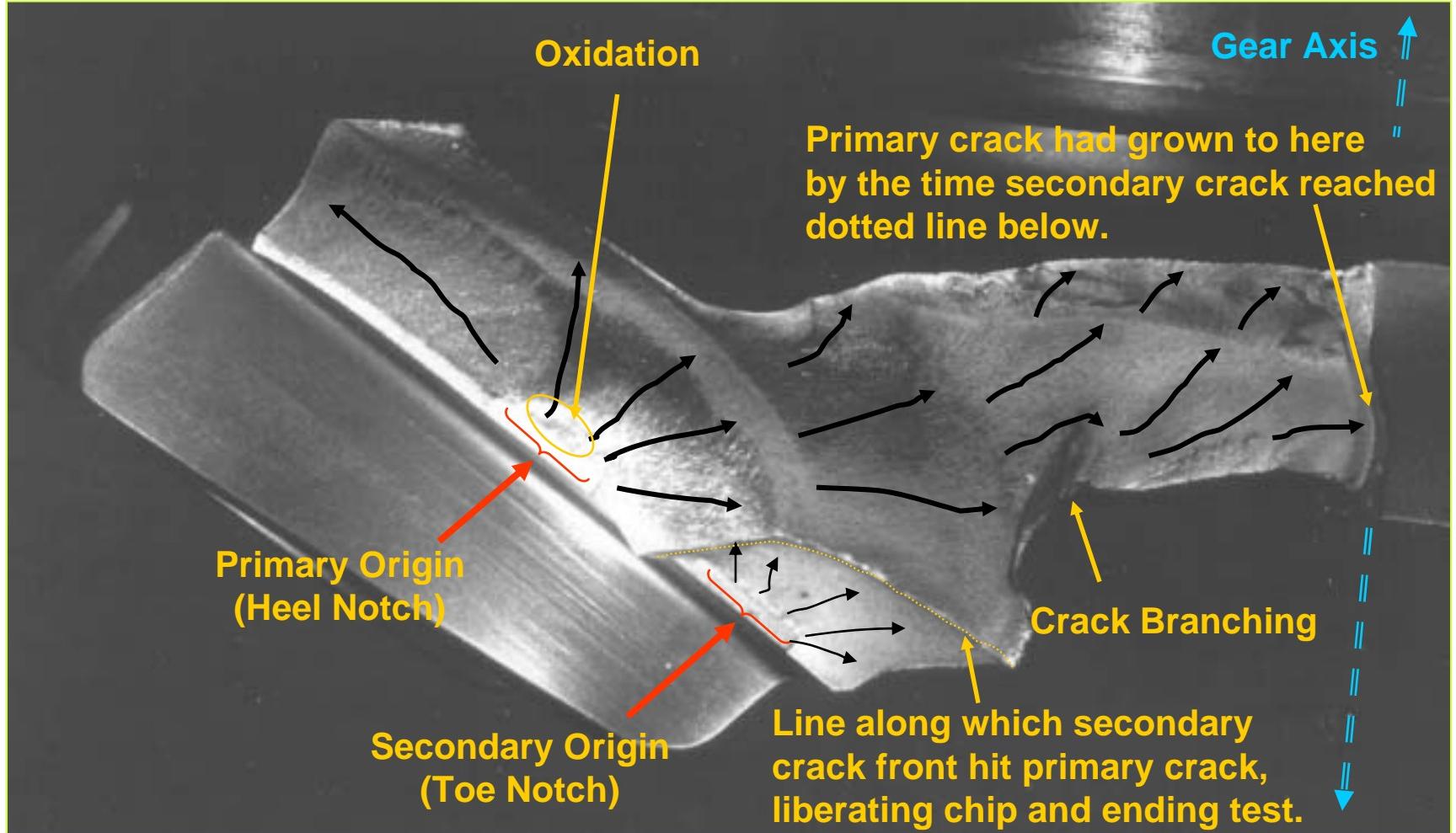
Image of heel notch outer end after Run 18 (first test), showing obviously visible crack (arrow).

# H-60 IGB Pinion Gear Mag Particle UV Image



# H-60 IGB Pinion Gear Mag Particle UV Image



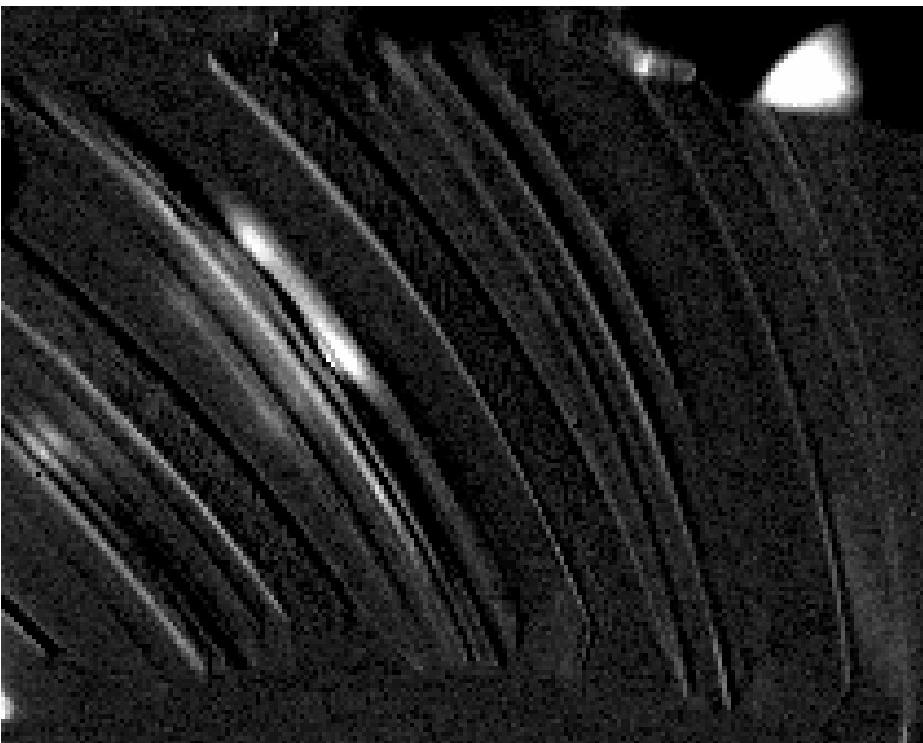
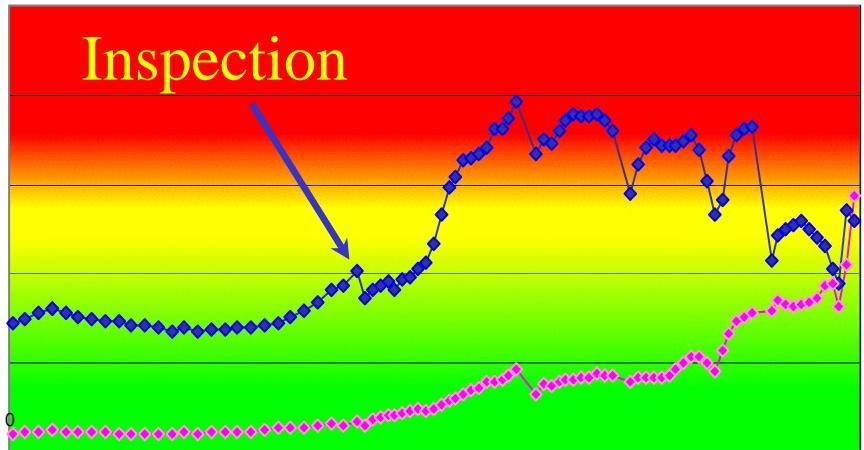


# Thermosonic Imaging

## Wayne State University

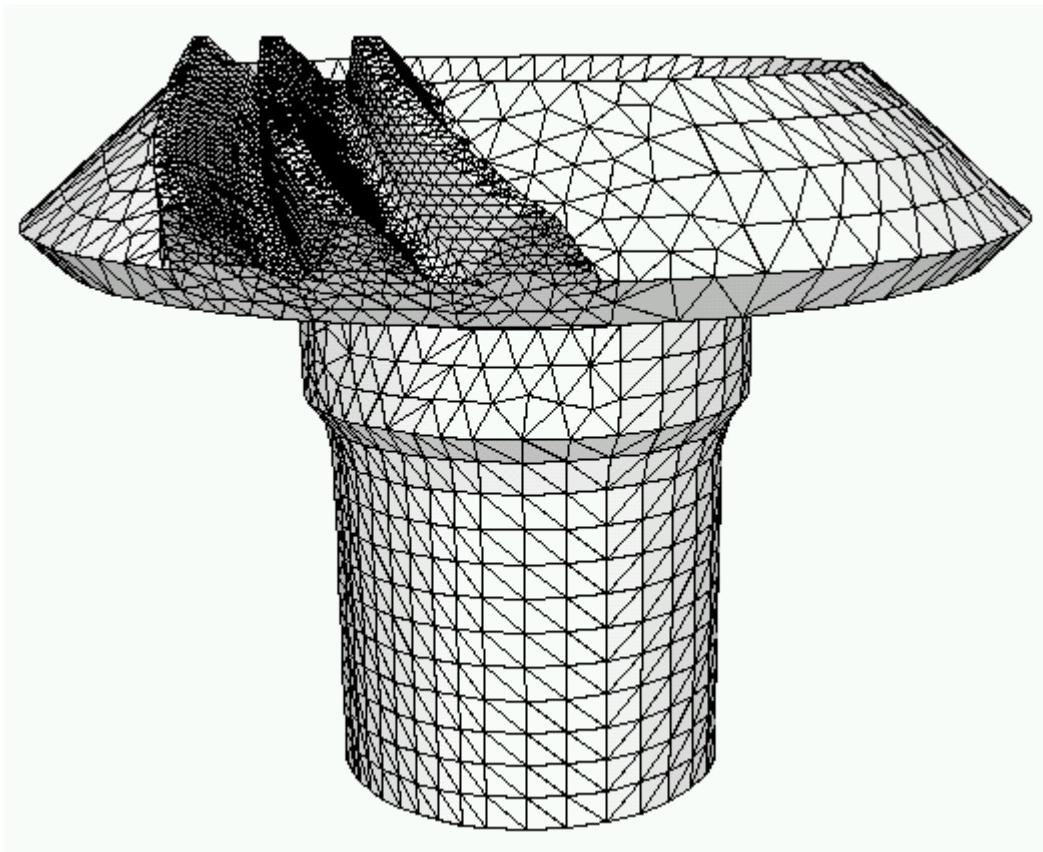
### ***Second test of IGB Pinion***

- Test Suspended upon detection of initial vibration indicator response
- Thermosonic imaging shows sub-surface crack
  - Located underneath the heel notch
  - Toe notch shows no damage

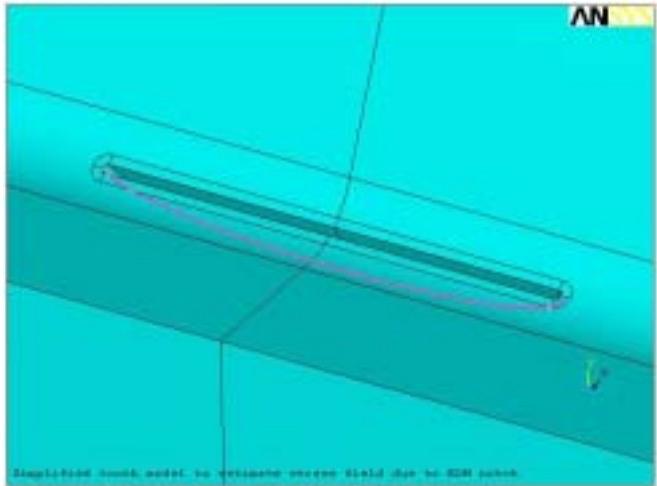


# Model of the Failure AERA and Impact SBIRs

Finite Element Mesh for  
IGB Pinion



3-D Solid Model of the  
EDM Notch



# Fracture Surface Trajectory Actual vs Computed



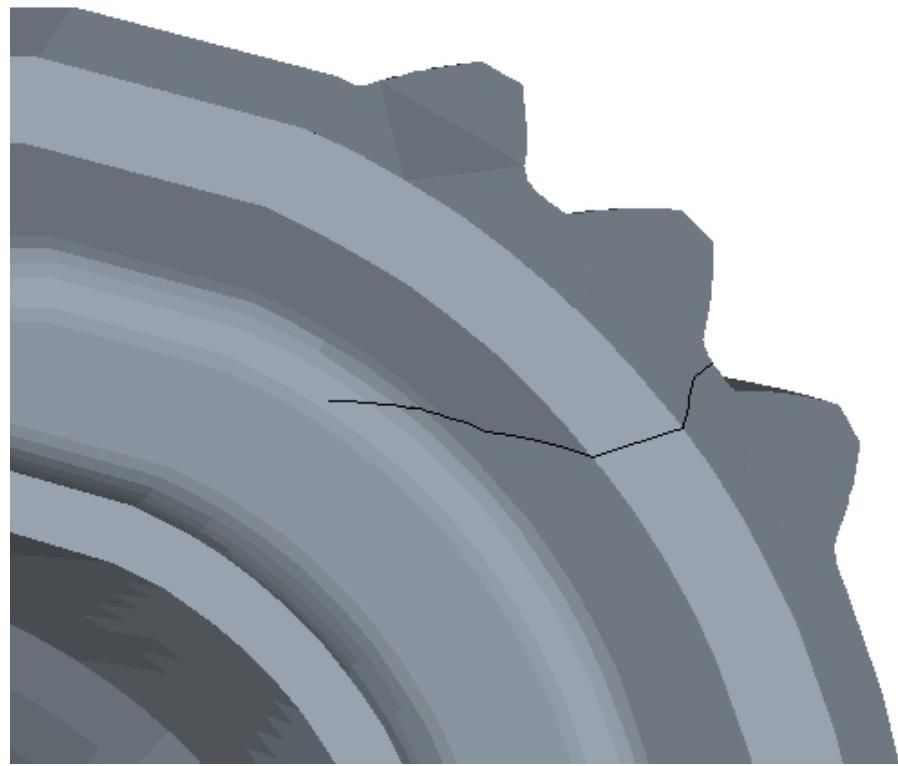
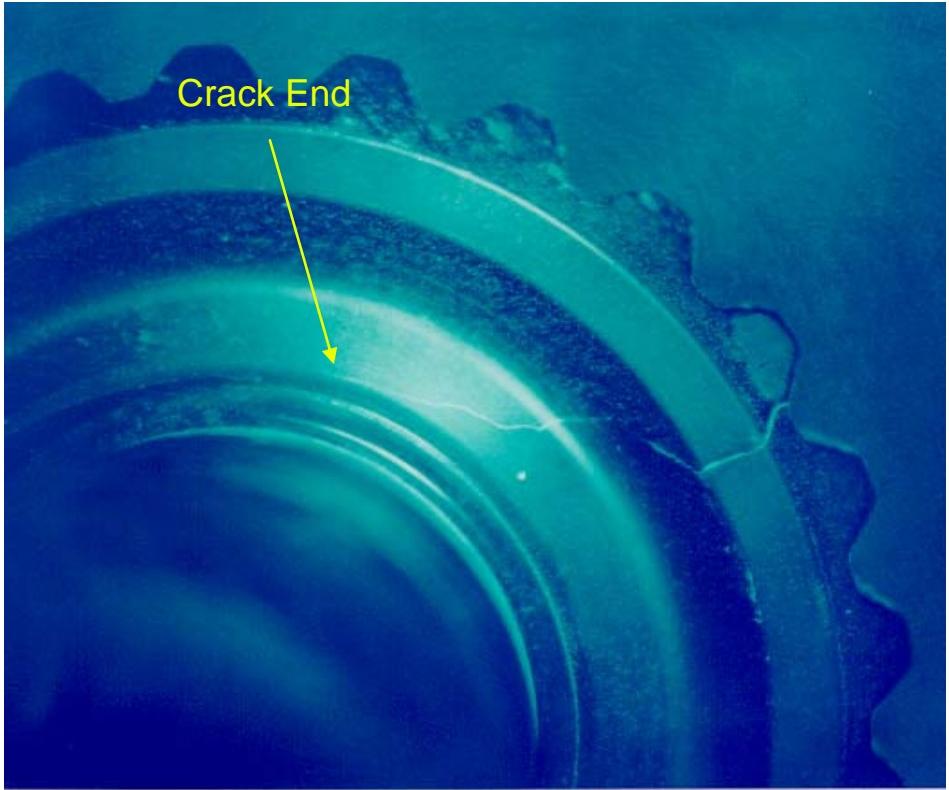
Propagation through  
the tooth area

**FRANC3D** Code used for  
Impact and AERA Efforts



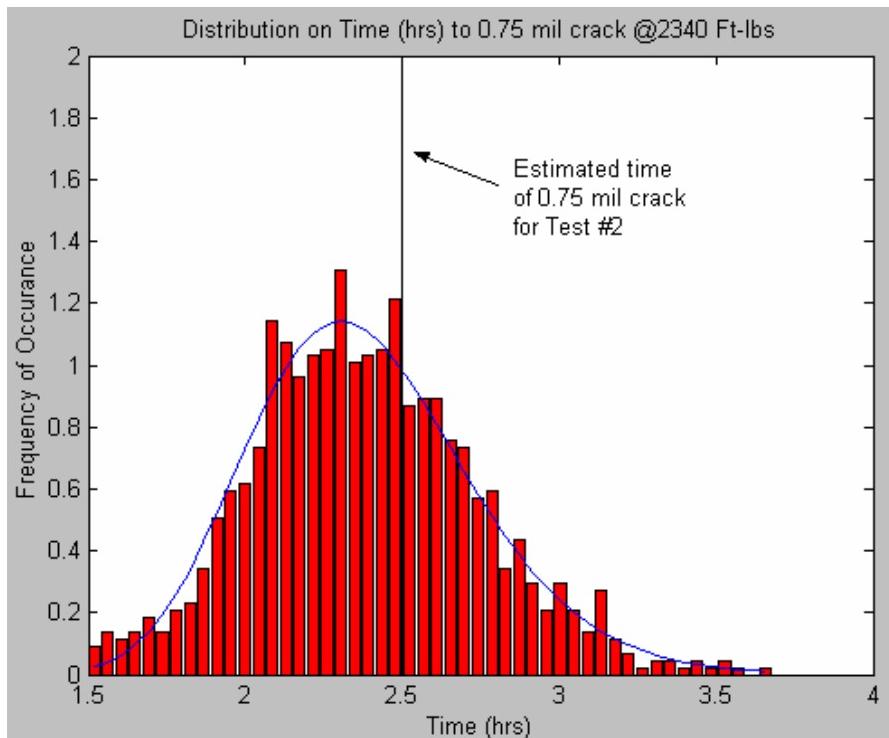
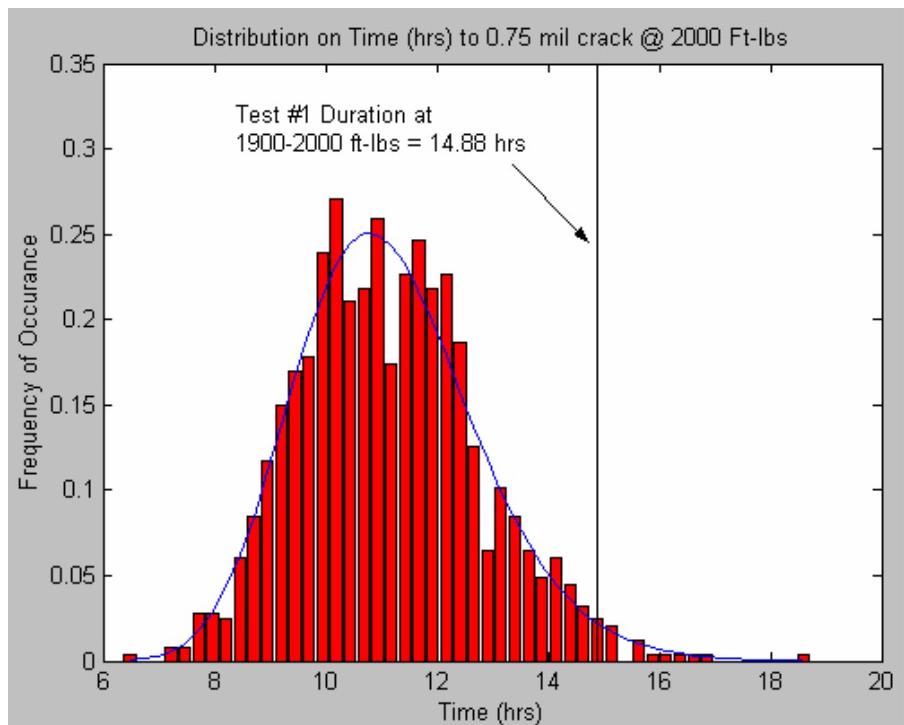
# Fracture Surface Trajectory Actual vs Computed

Propagation through the web area

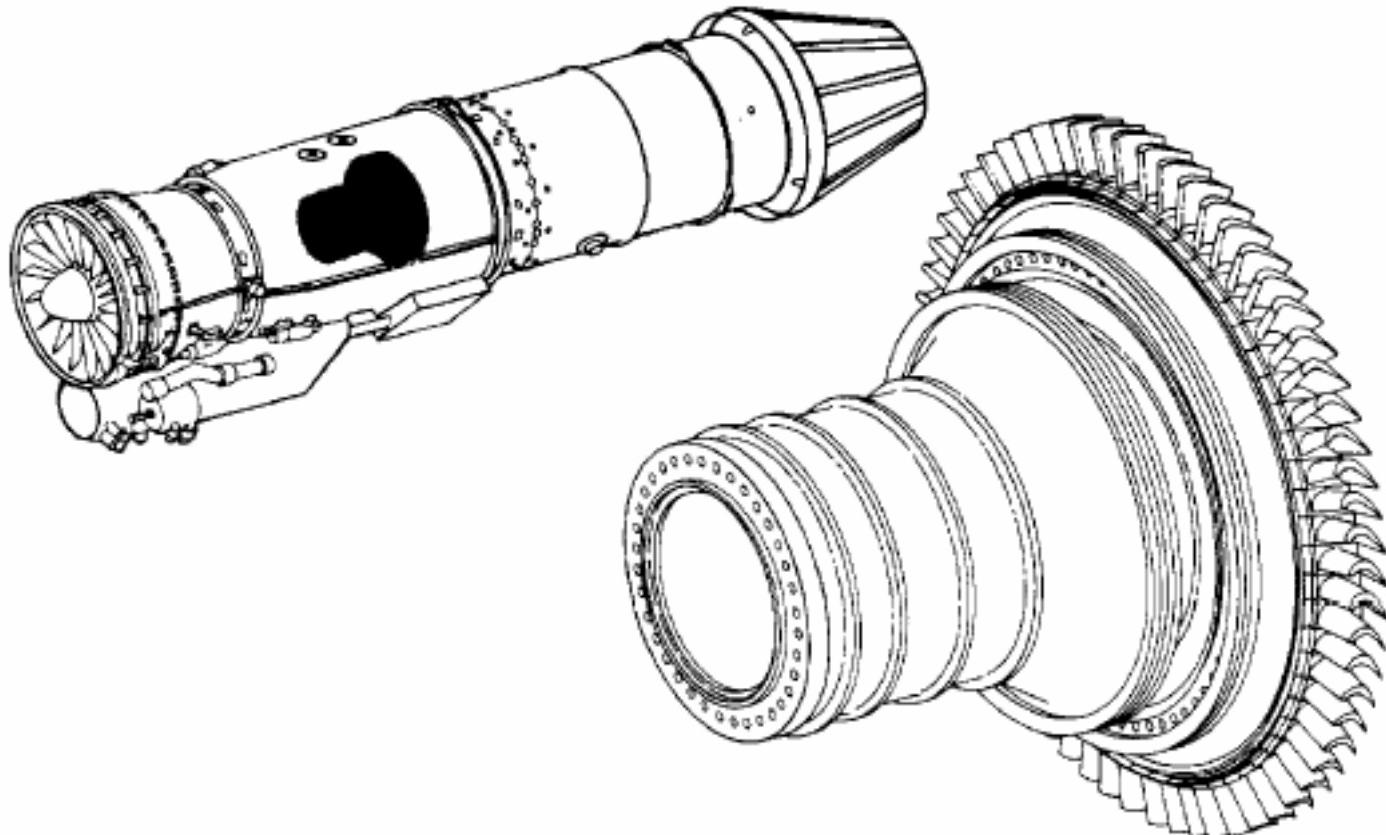


# Probability of 0.75 mil Crack Impact Technologies Model

- Fractographic analysis used to estimate total run time to presence of 0.75 mil crack
- Test 1 operating profile more complex than test 2
- Model predicts 98% probability of 0.75 mil crack for test 1 and 63% probability for test 2



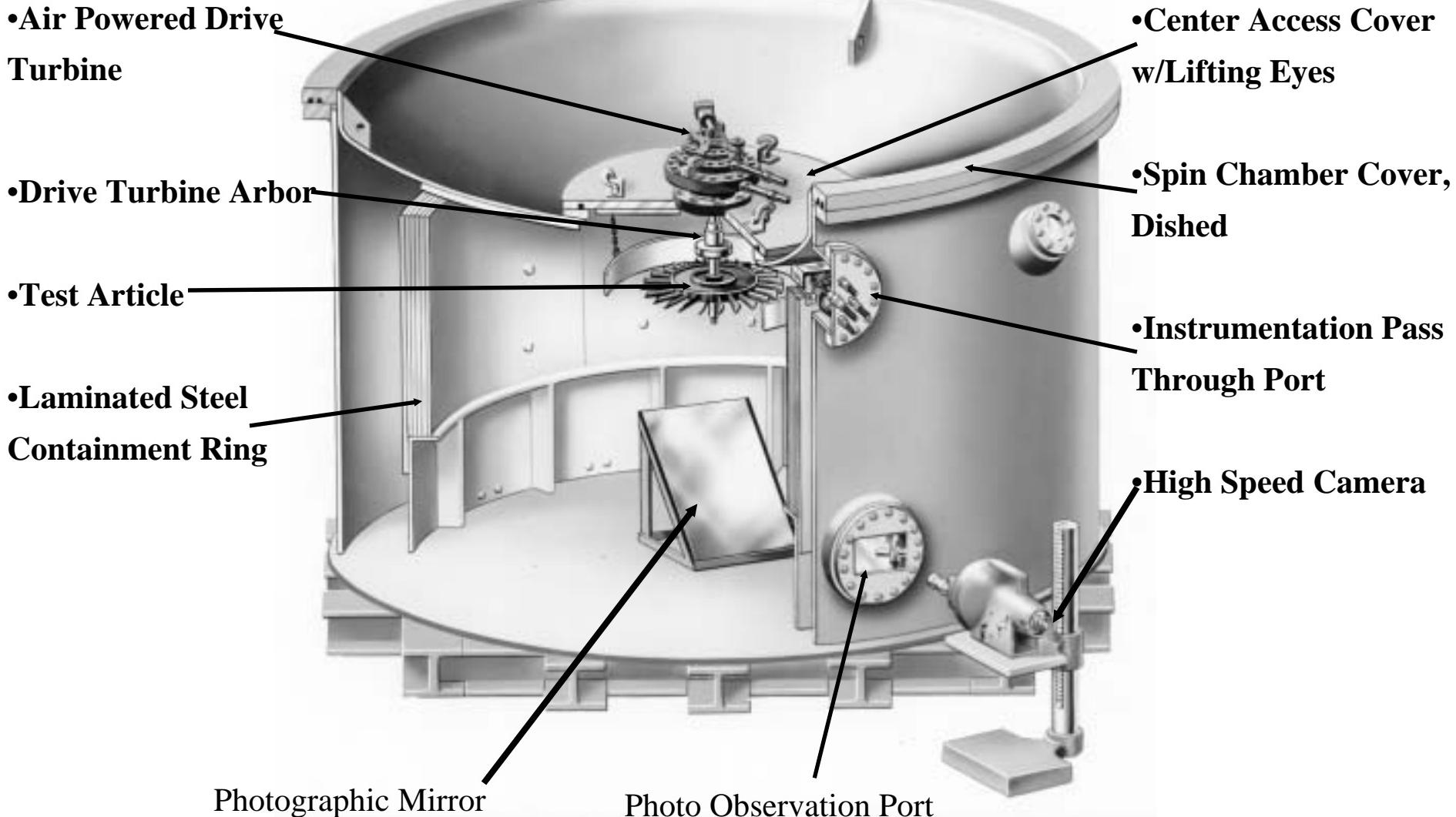
# Current DARPA Program RSF Test Article



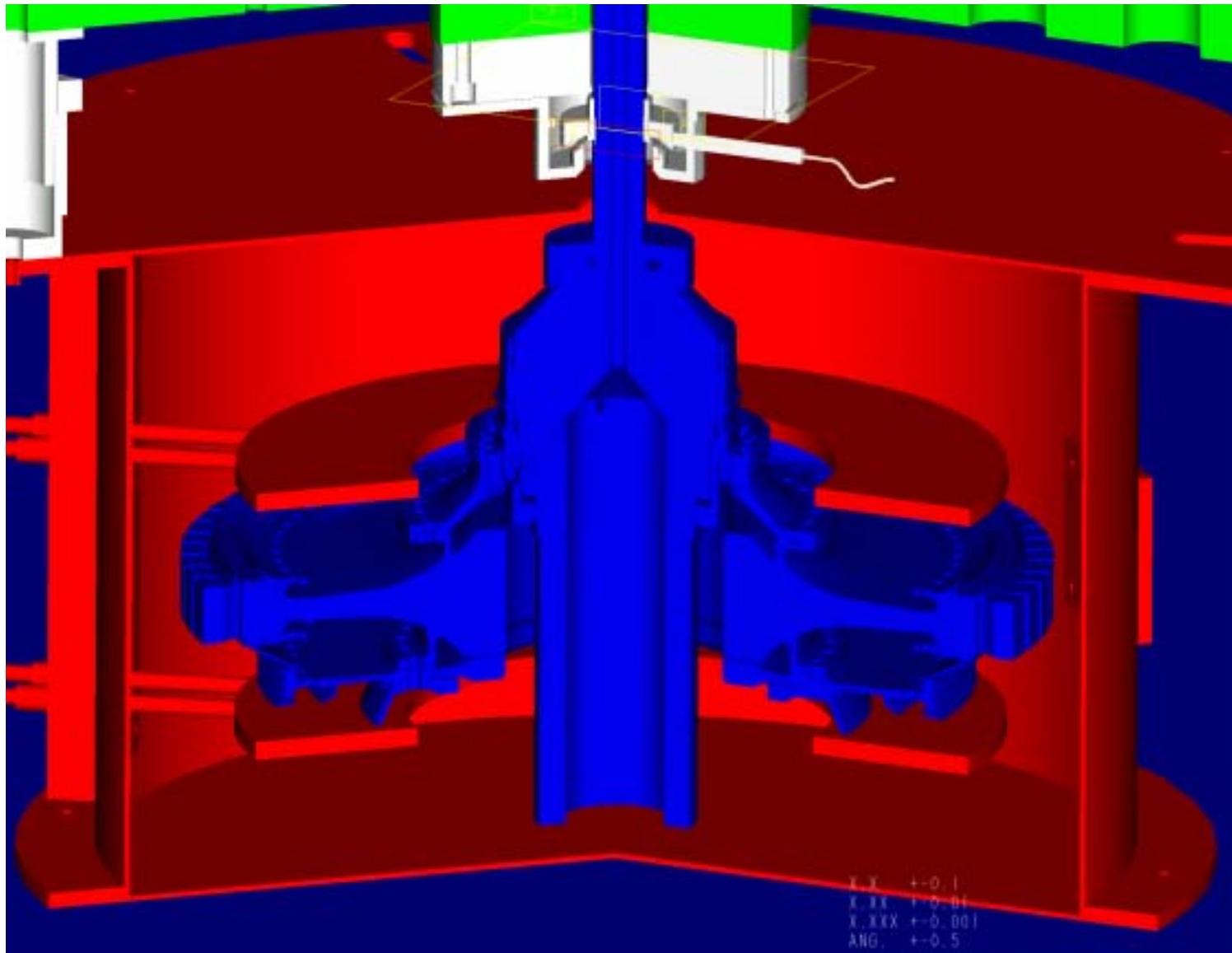
F404 High Pressure Turbine

# PAX River Rotor Spin Facility

## Spin Chamber Configuration



# Rendering of Test Article Installed in Rotor Spin Facility



- Multiple failure mechanisms incorporated
  - Low Cycle Fatigue
  - Dwell
- Multiple test articles each with several flaws
- Exercise current life models
- Incorporate latest advances in modeling
- Utilize state awareness sensors to detect developing cracks
- Develop integrated models which incorporate crack detection sensor outputs to recalibrate life models
- Predict crack growth behavior as accurately as possible

- State Awareness, Modeling, Material Science/Physics, Reasoning are integral to achieving prognostics
- Initial proof of concept work demonstrates some fundamental concepts central to achieving the prognosis vision
- We are just getting started!